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I. PURPOSE

The goal of this work is to (1) develop a system-level understanding of Radio Frequency (RF) microelectromechanical systems (MEMS) device integration into space applications, (2) identify relevant failure mechanisms of emerging RF MEMS switch technologies in space applications, and (3) develop testing methodologies for device qualification of RF MEMS switches.

II. INTRODUCTION

MEMS Technology

MEMS is the integration of electrical and mechanical devices at the centimeter (10^{-2} m) to micrometer (10^{-6} m) scale on the same chip, similar to an integrated circuit (IC). The essence of MEMS is their ability to sense and act on the surrounding environment utilizing micromechanical structures controlled by microcircuits. MEMS devices find applications in the automotive, medical, aerospace, defense, and telecommunications industries as sensors, actuators, and transducers, with sensors forming the largest segment. Although numerous MEMS devices have been commercially manufactured for over a decade, they are not considered an established technology, except for certain niche applications such as accelerometers in automobile air-bag deployment, inkjet printer heads for computer printers, and micro mirrors for projection displays. Table 1¹ provides a summary on the development history of MEMS devices. Many MEMS devices are still under development by various military, academic, and private organizations for integration into application-specific systems.

MEMS and IC devices share many of the same batch processing techniques such as lithography, wet and dry etching, e-beam evaporation, and chemical vapor deposition, with just a few unique variations or added processes to create the final 3-D structures, i.e., cantilevers, gears, membranes, and micro channels. The expertise to mass-produce the wide range of MEMS devices for all of their potential applications is still in its infancy, stimulated by research funded by corporations and Government agencies. Unlike integrated circuits, MEMS devices must be protected from the environment with which they interact due to their inherent sensitivity to humidity and particulate contamination. For this reason most MEMS devices are encapsulated in hermetically sealed packages, a costly attribute. The behavior of materials in response to simultaneous mechanical and electrical interactions at the micro-scale is under investigation, and there are still many material, fabrication, and packaging issues that have yet to be resolved before the MEMS family reaches maturity.

Table 1. Commercialization of Selected MEMS Devices

Product	Discovery	Evolution	Cost Reduction/Application Expansion	Full Commercialization
Pressure Sensors	1954-1960	1960-1975	1975-1990	1990-Present
Accelerometers	1974-1985	185-1990	1990-1998	1998
Gas Sensors	1986-1994	1994-1998	1998-2005	2005
Photonics Displays	1980-1986	1986-1998	1998-2004	2004
Bio/Chemical Sensors	1980-1994	1994-1999	1999-2004	2004
RF Switches	1994-1998	1998-2001	2001-2005	2005
Rotation Sensors	1982-1990	1990-1996	1996-2002	2002
Micro-Relays	1977-1982	1993-1998	1998-2006	2006

Space Applications

NASA recognizes the impact MEMS technology can have on space applications. Space systems that can utilize MEMS devices are listed in Table 2.

Table 2. MEMS Devices for Space Systems

System	Sub-System	MEMS Devices	Benefits
Propulsion	Ion-thruster	Micro thruster	Low mass Low power consumption Increased performance
Science Data Collection	Quadrupole mass spectrometer Radiometer	Bio/chemical sensor RF switch	
Telemetry	Microwave communications	RF switch	
Orientation	Attitude adjustment	Rotation sensor	

The New Millennium Program's ST-5 and ST-6 spacecraft are planned to host a propulsion system and the Inertial Stellar Compass Instrument designed using MEMS technology components to validate their performance in space. Compass technology uses an active pixel sensor in a wide-field-of-view miniature star-camera, often referred to as a "star tracker," and a MEMS-based inertial navigation guidance system. MEMS technology is one of the system enablers for the pico- and nano-satellites planned for future low earth orbit and interplanetary missions, resulting in reduced mass and power budget demand. All spacecraft systems must be able to withstand both the launch and orbit environments.

MEMS Reliability Concerns

The main obstacle hindering rapid integration of new technologies into critical systems is the inherent risk resulting from unproven reliability. Reliability, the ability of a device or system to maintain performance requirements throughout its mission lifetime, is a major factor for selecting devices for space flight applications. Space mission duration can be anywhere from 3 to 10 years or more for interplanetary missions, with spacecraft and accompanying instruments subject to mechanical shock, vibration, temperature, vacuum, and radiation conditions, induced by launch, orbiting, and interplanetary travel environment. These factors are not tested for in commercial foundries or research institutions unless developed for a specific space application or until a program deems the technology necessary for mission success. MEMS offers the advantage of tremendous reductions in mass and power that will translate into significant cost benefits to NASA projects if realized.²

To understand system reliability, failure mechanisms, along with the resulting failure modes, must be correctly identified. In the microelectronics industry, many of these failure mechanisms are well understood and can be simulated in a laboratory setting through accelerated testing. MEMS failure modes and mechanisms are still being researched; however, there are certain fundamental modes that have been witnessed throughout the MEMS community in the terrestrial environment as listed in Table 3.

Table 3. MEMS Operational Failure Modes and Mechanisms

Failure Mechanism/Mode	Definition	Aggregate
Stiction	The adherence of two polished surfaces in contact with each other caused by the formation of strong primary bonds, mechanical action; two polished surfaces come into contact they tend to adhere to one another.	Planar surfaces in contact Humidity Dielectric charging
Wear	The removal of a material from a solid surface as the result of a mechanical action.	Rubbing surfaces Repetitive contact
Fatigue	Caused by the cyclic loading of a structure below the yield or fracture stress of a material.	Repetitive application of force
Fracture	Occurs when load on a device is greater than the strength of the material.	Mechanical overstress

III. RF MEMS SWITCHES

Theory

RF MEMS switches are very simple actuators utilized in applications where routing, phase changing, or simple on-off functions of RF signals are necessary. Typical applications include transmit/receive switching in a system with one antenna, channel selection in a wideband receiver, and digital modulation of RF signals. RF MEMS switches can replace solid-state electronic microwave switching devices such as Positive-Intrinsic-Negative (PIN) Diodes and GaAs Field Effect Transistors (FETs). PIN diodes can operate at nanosecond switching speeds however their power handling capabilities are limited. GaAs FETS are up to 50 times faster than PIN diodes, but signal degradation is increased. RF MEMS switches are slower, microsecond switching speed, with limited power handling capability typically less than 500 mW, but signal degradation is nominal and bandwidth is increased. At this time, RF MEMS Switches are appropriate for low power handling, KHz switching applications of DC-40 GHz RF signals. Table 4³ compares the parameters of MEMS and solid-state RF switch technologies.

Table 4. Comparison of Solid State with MEMS RF Switches

	PIN Diode	GaAs MMIC	MEMS
Switching Speed (S)	10^{-9}	10^{-9}	10^{-6}
Voltage (V)	5	N/A	3-50
Contact Resistance (Ω)	1	N/A	3-5
Loss @ 1GHz	0.5-1	1.1	0.1
Isolation @ 1 GHz	40	60	> 40
Bandwidth (GHZ)	0.02-2	0.005-4	DC-40

Because RF MEMS can be integrated with many semiconductor technologies, i.e., Gallium Arsenide and Silicon, MEMS switches allow for a higher level of integration leading to a reduction in mass and simpler interconnections. RF MEMS switches are usually either two fixed end (bridge, membrane) or one fixed end (cantilever) in structure and either ohmic or capacitive in operation. Although there are many types of actuation methods (e.g. thermal, electromagnetic), this paper's focus is on electrostatically actuated switches. The two specific types of switches tested in this work are (1) ohmic cantilever, and (2) capacitive membrane. Both switches have the same mechanical model as illustrated in Figure 1. Switches are modeled as a single rigid parallel plate capacitor suspended above a fixed ground plate by an ideal linear spring. The structure, material, and fabrication process of the upper plate determines the spring constant, K; g is the distance between the top structure (beam, membrane) and the bottom electrode; and V is the voltage applied to the bottom electrode. (See Figure 1.)

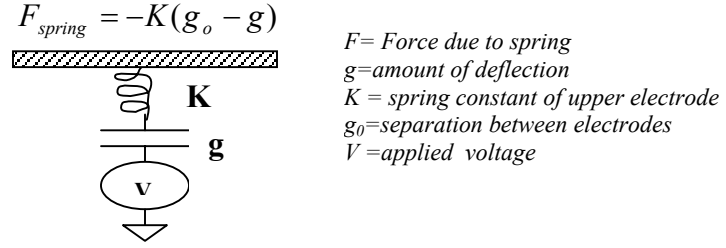


Figure 1. Mechanical Model of MEMS Switch

Cantilever switches consist of a thin strip of metal suspended over a metallic transmission line with a gap of a few microns. Underneath the cantilever is another electrode that serves to pull down the cantilever until the tip touches the transmission line closing the circuit (See Figure 2).

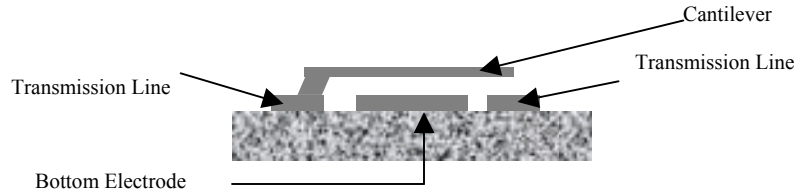


Figure 2. Basic Ohmic Cantilever Structure

For ohmic switches, open-circuit no-contact state is “off” and closed-circuit contact state is “on”. Basic equations for the ohmic cantilever switch are as follows:

$$\delta = 6 \frac{F(1-\nu^2)L^3}{E} \frac{L^3}{Wt^3}$$

δ = deflection of beam tip
 F = electrostatic force
 ν = Young's Modulus of beam
 W = width of beam
 L = length of beam
 t = thickness of beam

$$F = \frac{\epsilon_0 A V^2}{2g^2}$$

F = electrostatic force needed to actuate switch
 A = effective area of the capacitor
 V = applied voltage
 g = physical separation between contacts
 t = thickness of beam

For the capacitive switch, the two states are realized by a low, 10^{-15} farad range; up-state capacitance, C_{up} , for “off”; and a high, 10^{-12} farad, down-state capacitance, C_{down} , for “on” (Figure 3).

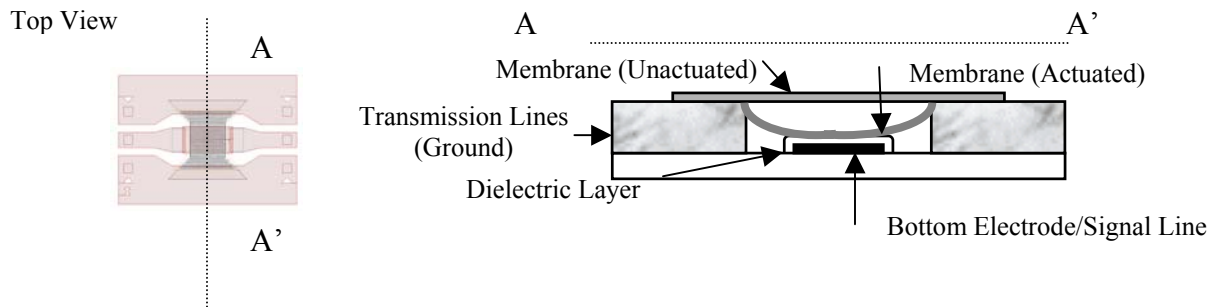


Figure 3. Basic Capacitive Membrane Structure

The following equations are used to determine the up and down state capacitance of the MEMS Capacitive

Membrane Switch:

$$C_{up} = \frac{1}{\left(\frac{h_D}{\epsilon_D} + \frac{h_a}{\epsilon_a}\right)} \quad C_{down} = \frac{\epsilon_D A}{h_D}$$

C_{up} = up-state capacitance
 C_{down} = down-state capacitance
 h_D = height of dielectric
 h_a = height of air gap
 ϵ_D = dielectric constant of dielectric material
 ϵ_a = dielectric constant of air
 A = effective area

The dielectric serves to reduce metal-to-metal stiction problems in the switch. Applying a voltage to the bottom electrode creates an attractive electrostatic force, due to the difference in potential, causing the membrane to snap down onto the dielectric layer. In the up position, the low capacitance value creates a high impedance, making it very difficult for high- frequency signals to pass. Once the membrane snaps down, high-frequency signals are capacitively coupled and are allowed to propagate through the signal line.

Reliability in Space Applications

The most observed failure mode in RF MEMS switches in the terrestrial environment is stiction. In ohmic switches, stiction is a result of microcrystalline surfaces in close contact and high RF power (>500 mW) operation. In capacitive membrane switches, stiction is caused by charge buildup, dielectric charging, in the thin dielectric layer that also causes switches to self-actuate. Dielectric charging results from high voltages applied to operate the switch. The aforementioned failure modes are associated with terrestrial operating conditions. For space applications, further environmental concerns must be addressed to ensure mission success in addition to operational issues. Table 5⁴ outlines these issues.

Table 5. MEMS Environmental Failure Modes and Mechanisms

Environmental Stress	Concern
Shock/Vibration	Failure during launch and/or travel to orbit
Vacuum	Failure in orbit
Radiation	Insulator Charging
Temperature/ Thermal Cycling	Effect on temperature sensitive material properties
Atomic Oxygen	Formation of insulating compounds

Further investigations need to be performed before the breadth of MEMS devices can be integrated into space systems. However, certain specific components can be evaluated for their technology readiness and implemented once performance is proven. RF MEMS switches are poised to become the next widely commercially available

MEMS devices. NASA can take advantage of this technology in its space communications and microwave remote sensing systems.

IV. TEST APPROACH

Testing will be conducted in the lab facilities of Code 562. Ohmic cantilever switches have been packaged while the capacitive membrane switches are bare die. The test flows are provided below.

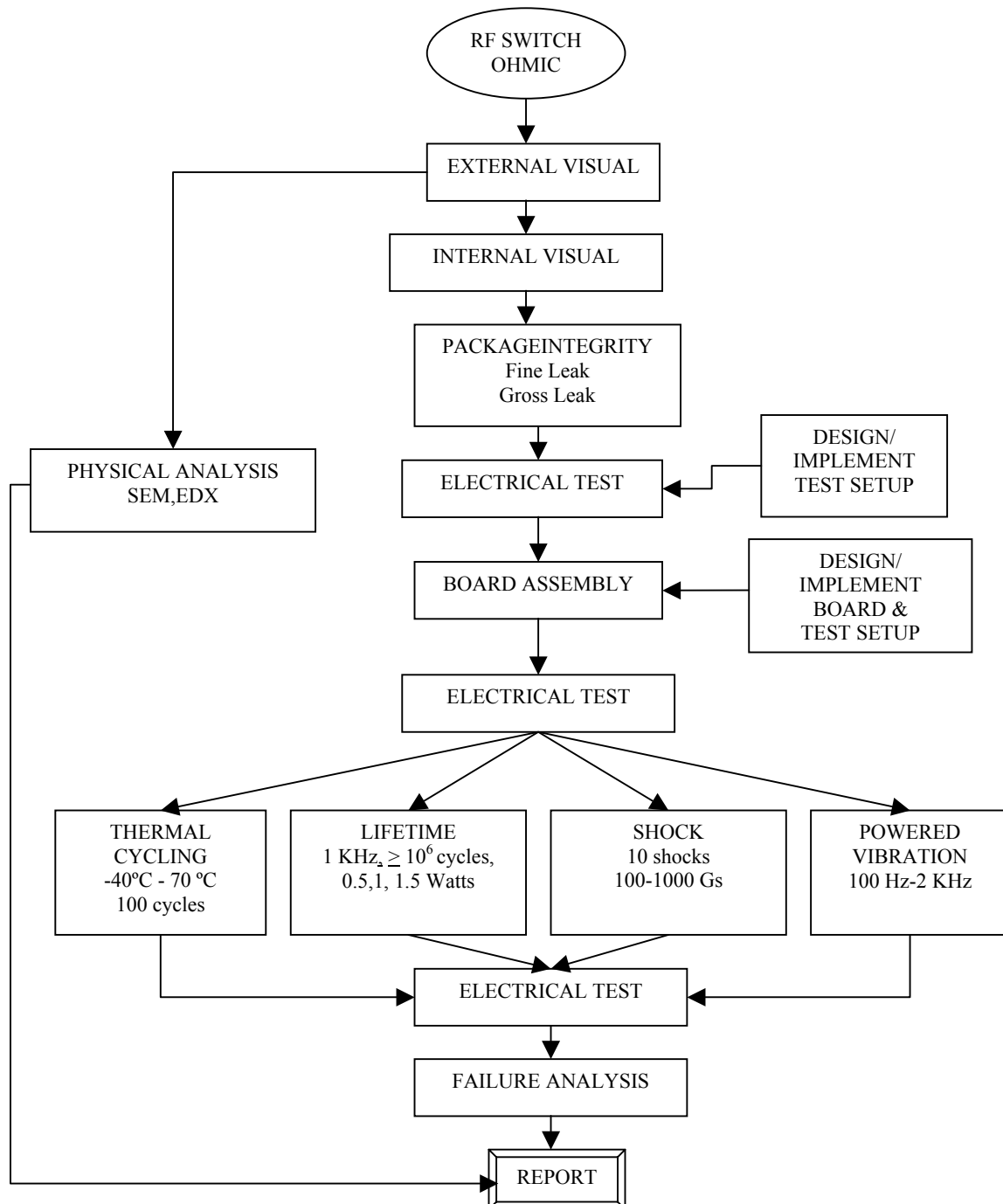


Figure 4. Test Flow for Commercial Switch

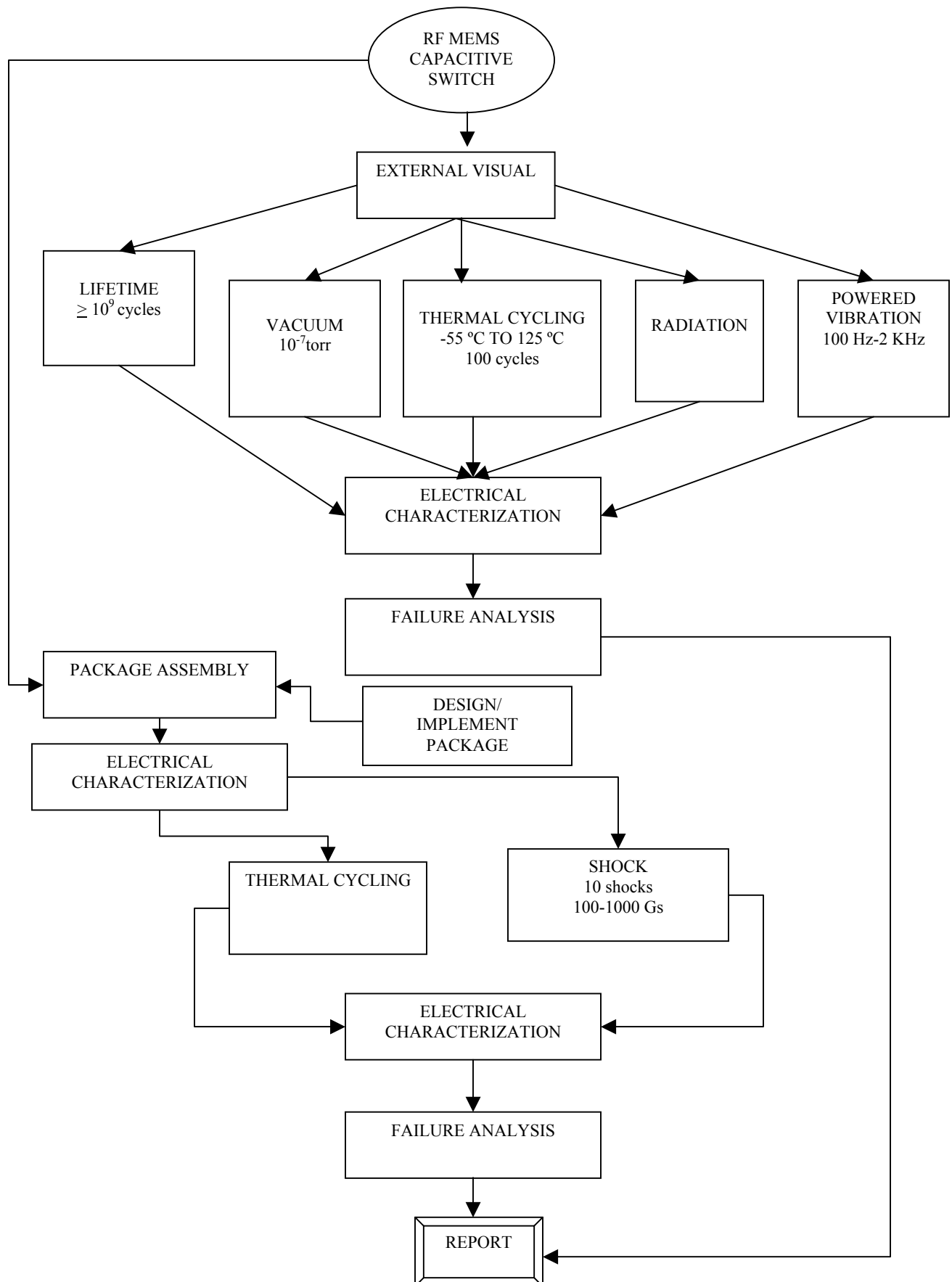


Figure 5. Test Flow for Capacitive Membrane Switch

As stated before, the main lifetime-limiting factor in RF MEMS Switches is stiction which has been verified through numerous papers published on the subject.^{5,6,7,8} MEMS failure mechanisms specific to the space environment are still under investigation with work being done on microrelays,⁹ accelerometers, RF switches, and micro-engines proving that subjection to vacuum, mechanical shock, and radiation environments will result in performance degradation and/or hard failures. Switches will be evaluated for performance and reliability under operational stresses and environmental stresses including actuation lifetime, thermal cycling, powered vibration and mechanical shock to determine their effects on RF MEMS switch operation.

V. RF MEMS CAPACITIVE MEMBRANE SWITCH (GSFC)

Description and Operation

RF MEMS capacitive membrane switches were developed by Codes 555, Microwave Instrument Technology Branch, and are under fabrication by Code 553, Detector Systems Branch, through a DDF (Director's Discretionary Fund) grant. RF MEMS capacitive switch cross-section and material make-up is shown below in Figure 6.

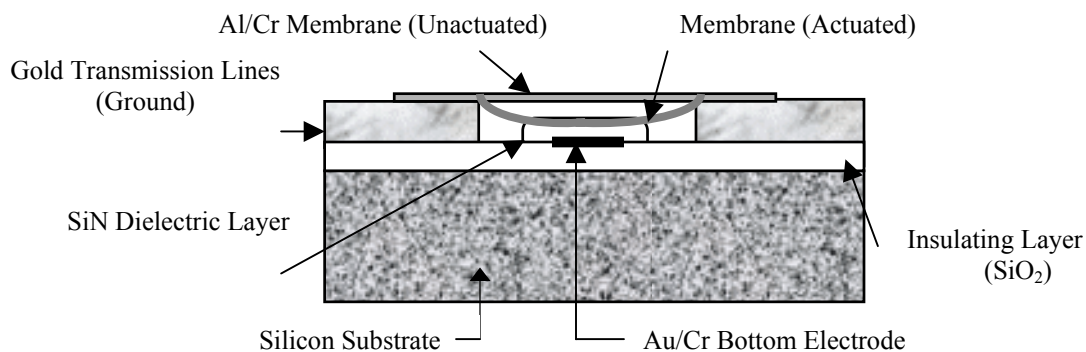


Figure 6. GSFC RF MEMS Capacitive Membrane Switch

A 1 μm layer of silicon dioxide layer was thermally grown on a high resistivity Silicon wafer. Gold (Au)/Chromium (Cr) is deposited and patterned for the bottom electrode (400 μm x 70 μm), followed by electron cyclotron resonance chemical vapor deposition (ECR-CVD) of the 0.3 μm layer of Silicon Nitride (SiN). Transmission lines are deposited and patterned followed by application of sacrificial polymer layer. The aluminum (Al) -Cr membrane is deposited on top of the sacrificial layer, which is subsequently removed through oxygen plasma etch resulting in the final structure with a 3.5 μm air gap. All metals are deposited by e-beam evaporation. Wafers contain several different membrane geometries to optimize performance. The actuation voltage of switch is in the range of 60 V to 80 V with a $C_{\text{off}}/C_{\text{on}}$ of 175.

It is designed to achieve minimal insertion loss for use in radiometer applications.

Specific Applications and Advantages

RF MEMS switches being fabricated at NASA GSFC are targeted for microwave instruments, specifically Dicke Radiometers. Dicke radiometers are used in microwave remote sensing of Earth in the frequency range of 1 GHz to 40 GHz. A schematic Diagram of a Dicke Radiometer is shown in Figure 7.

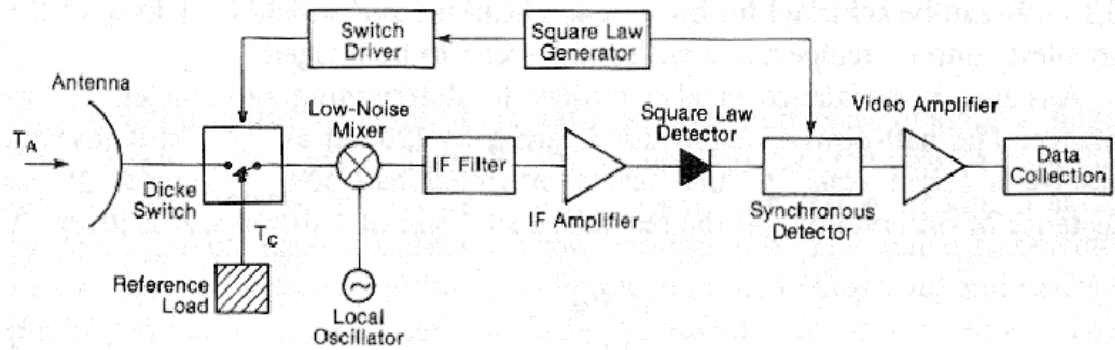


Figure 7. Dicke Radiometer Schematic

RF MEMS switches are used as a Dicke switch in a Dicke radiometer; radiometer is a passive microwave detector. Input to the system is switched between measured data and a well-known reference load to accurately characterize gain. Accurate characterization of the erratic gain fluctuations imposed by the electrical system increases the accuracy of the measured scientific data. Depending on the amplifier technology used, switching speeds range from 10 Hz to 10 kHz. Current technology utilizes GaAs FET or PIN Diodes, very lossy devices that degrade an already weak signal. Table 6 provides performance comparisons of RF MEMS Switch technology versus GaAs FET and PIN diodes for switching speed, insertion loss and power consumption parameters,

Table 6. Parameters for Dicke Switch Technology

Technology	Switching Speed	Insertion Loss	Power Consumption
GaAs FET	5 – 100 ns	< 4 dB	2100 mW
PIN Diode	10 – 100 ns	< 1.9 dB	3 –100 μ W
RF MEMS Switch	< 100 μ s	< 0.4 dB	2 μ W–1.7 mW

As can be seen, MEMS switches offer a 5 to 10 time reduction in insertion loss (amount of signal degradation). Although the switching time is slower, these speeds are adequate for most microwave remote-sensing applications,

switching at an expected 1 KHz to 10 KHz range. Switches are expected to operate into the billions of cycles. The performance advantages can be realized only if switches perform reliably in the mission-specific space environment.

VI. COMMERCIAL SWITCH

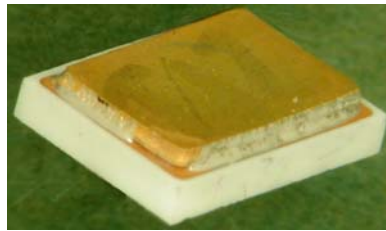
Teravicta is the only design house with RF MEMS switches currently poised for mass production. They have already partnered with Read-Rite Manufacturing, a mass producer of hard drives featuring MEMS technology. This makes them a viable option for investigation of relevant failure modes and mechanisms stemming from a relatively established processing technology. Teravicta's RF MEMS switches are reflective ohmic switches with specifications listed in Table 5. One evaluation board and 20 switches were procured from Teravicta through Dow-Key. The devices came from two different lots, 10 from Lot 1 and 10 from Lot 2.

External and Internal Inspection

The TT612 Teravicta switches were subjected to non-destructive analysis. Evaluation included optical inspection, x-ray, and leak testing. The parts were examined optically, and several of the parts exhibited chip-outs in the white ceramic base. Radiography was performed for internal inspection. Inspection of the lid seal showed many voids in the solder material, some of which span more than 75% of the lid seal area, cause for rejection under MIL-STD-883. Voids could indicate poor manufacturing processes.

Table 7. Teravicta TT612 RF MEMS SPDT Switch Manufacturer Specifications

PARAMETER	UNITS	VALUE
Frequency Range	GHz	0.3 - 6
Actuation Voltage	V	60 V
RF Power Max	W	2
Insertion Loss (frequency dependent)	DB	0.09 - 0.26
Isolation (frequency dependent)	dB	> 19
Return Loss	DB	0.09-0.26
Switching Time	μs	< 60
Actuations Before Failure		10 ⁶
Ron (Series Resistance)	Ω	0.5
Operating Temperature Range	° C	0 - 70
Storage Temperature	° C	-40 - 70



(A) TT612 RF MEMS switch showing metal cap and alumina bottom of hermetically sealed CSP



(B) Bottom of TT612 showing surface mount contact pads

Figure 8. Teravicta TT612 SPDT Switch in Chip Scale Package

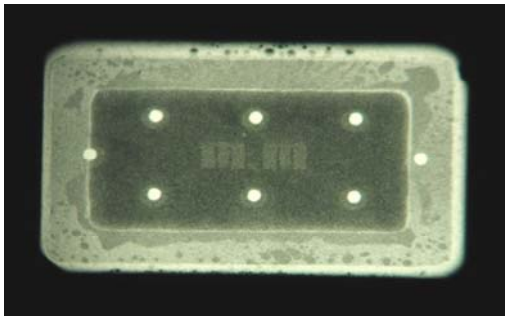


Figure 9. A top-down x-ray of the part reveals extensive voiding in the lid seal material. The MEMS switch is located at center.



Figure 10. The void at location '1' spans more than 75% of the lid seal area. However, no leaks were found during either fine or gross leak testing.

Seal Integrity

Fine leak and gross leak testing was performed according to MIL-STD-883 on all 20 parts. All parts passed according to the military standard.



Figure 11. A tilt view of SN10 reveals an erratic solder fillet between the arrows, suggesting possible loss of hermeticity.

Table 8. Fine and Gross Leak Test Results

Device	Fine Leak 5×10^{-8} atm cc s ⁻¹ (maximum)	Gross Leak
1	4.0×10^{-9}	Pass
2	4.0×10^{-9}	Pass
3	4.0×10^{-9}	Pass
4	3.5×10^{-9}	Pass
5	4.0×10^{-9}	Pass
6	3.5×10^{-9}	Pass
7	3.5×10^{-9}	Pass
8	2.5×10^{-9}	Pass
9	2.5×10^{-9}	Pass
10	2.5×10^{-9}	Pass

Electrical Tests

After nondestructive analysis, devices were subjected to electrical characterizations, to see how well the devices performed according to the manufacture specifications.

Table 9. Incoming Inspection Electrical Characterization Results of 10 Devices

		R _C Contact Resistance @ 60 V	V _A Actuation Voltage	V _R Release Voltage	T _{on} Turn on time
		OHMS	V	V	10 ⁻⁶ sec
	SPECIFIED	< 0.5	60	N/A	<50
1	RF1	0.6	44	31	*
	RF2	0.7	43	34	17.6
2	RF1	*	*	*	*
	RF2	0.6	44.5	34	20
3	RF1	0.7	48	32	26.2
	RF2	1.2	52	47	27.2
4	RF1	0.6	49	25	26.9
	RF2	0.7	48	42	25.5
5	RF1	0.5	46	39	20
	RF2	0.6	50	39	21.7
6	RF1	0.5	47	30	20
	RF2	1.7	50	45	27.3
7	RF1	0.5	47	30	24.6
	RF2	2.1	52	48	26.6
8	RF1	0.6	50	44	21.4
	RF2	0.9	47	40	20.9
9	RF1	1	50	44	26
	RF2	0.9	45	41	21.1
10	RF1	0.9	49	40	22.1
	RF2	0.9	47	40	22

As viewed in the data in Table 8, the contact resistance of the switches is high, which may be a result of improper testing or inherent to the device. Further investigation proved that DC testing , even at minimum levels, can affect device performance. No further DC Testing will be conducted.

Board Assembly

To enable RF testing, a 50 Ω impedance board was designed. The board was designed in house, and mounting of the devices were performed in house using a regular solder reflow process. The board was designed to enable testing with a HP8753E network analyzer to measure insertion loss, return loss, and isolation of each switch in the frequency range of 300 KHz to 6 GHz. Figure 12 shows assembled board connected to the network analyzer. After each environmental test, the RF switches will be characterized.

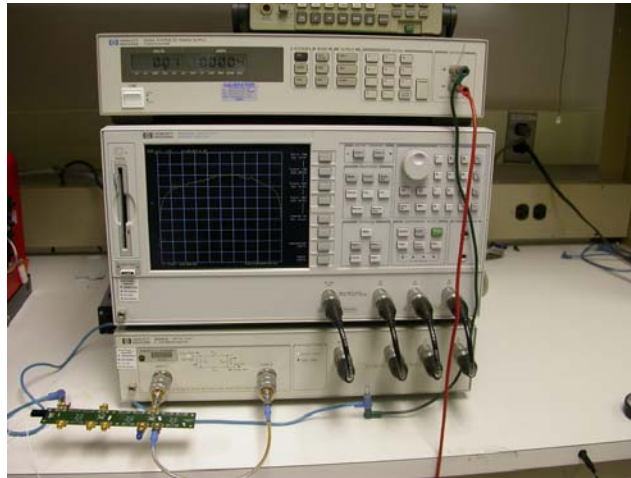


Figure 12. RF Board Connected to Network Analyzer

After validation of device performance, devices can be subjected to reliability/stress testing. The next step is mechanical stress testing in which devices will be subjected to mechanical shock and vibration environments. According to the manufacturer, the shock and vibration limits of the device have not been tested. The plan is to begin at lower limits for small time intervals and increase levels of both time and frequency as testing continues and limits are realized. Devices have been subjected to vibration frequencies from 100 Hz – 250 Hz, 20 g force, with no power, for duration of 5 seconds. From these initial tests, no significant damage was noted. Levels will be increased and testing will continue.

Physical Analysis

One device was delidded and examined under a scanning electron microscope (SEM) and analyzed using energy dispersive X-ray spectroscopy (EDX) to determine composition. The mechanical structure and electrodes are composed of gold (Au). A simple cantilever structure was believed to make up the throws of the switch; however, SEM analysis shows the structure is slightly more complicated. Analysis is ongoing.

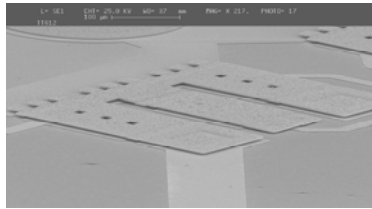


Figure 13. SEM Image of One Throw of the Switch

VII. SUMMARY

The packaging of the commercial device seemed questionable at first glance, however testing proved the integrity of the hermetic seal. RF electrical testing will be conducted as opposed to DC testing. So far, devices have been able to withstand low impact shocks and lower frequency vibrations. Structure of commercial device will be determined and used to evaluate response to environmental stresses.

Work will continue with RF MEMS switches to evaluate their suitability in space applications.

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